METHODS FOR ESTIMATING NON-ENERGY GREENHOUSE GAS EMISSIONS FROM INDUSTRIAL PROCESSES

October 1999

Prepared by:
ICF Consulting

Prepared for:
Greenhouse Gas Committee
Emission Inventory Improvement Program

ACKNOWLEDGMENTS

CONTENTS

CONTENTS (CONTINUED)

TABLES

1

INTRODUCTION

The purposes of the preferred methods guidelines are to describe emissions estimation techniques for greenhouse gas sources in a clear and unambiguous manner and to provide concise example calculations to aid in the preparation of emission inventories. This chapter describes the procedures and recommended approaches for estimating non-energy greenhouse gas emissions from industrial processes.

Section 2 of this chapter contains a general description of the emissions from this source category. Section 3 provides an overview of the steps involved in using the preferred methods for estimating emissions. Section 4 presents the preferred estimation methods in detail; Section 5 is a placeholder section for alternative estimation techniques that may be added in the future. Quality assurance and quality control procedures are described in Section 6. References used in developing this chapter are identified in Section 7.

2

SOURCE CATEGORY DESCRIPTION

2.1   EMISSION SOURCES

Emissions are often produced as a by-product of various non-energy related activities. Unlike the CO_2 emissions from combustion (described in Chapter 1 of this volume), these emissions are produced directly from the process itself. In some industrial sectors, raw materials are chemically transformed from one state to another. This transformation often results in the release of greenhouse gases such as carbon dioxide, nitrous oxide, hydrofluorocarbons, perfluorinated carbons, and sulfur hexafluoride. The production processes addressed in this section include: cement production, nitric acid production, adipic acid production, lime production, limestone use (*e.g.*, for iron and steel making, flue gas desulfurization, and glass manufacturing), soda ash production and use, carbon dioxide manufacture, aluminum production, HCFC-22 production, and sulfur hexafluoride use in electrical power systems.[1]

Greenhouse gases are emitted from a number of industrial processes not covered in this section. For example, CO_2 manufacture is a source of CO_2, and ammonia production is believed to be an industrial source of methane, nitrous oxide, and non-methane volatile organic compounds. However, emissions for these sources have not been estimated at this time due to a lack of information on the emission processes, the manufacturing data, or both. As more information becomes available, emission estimates for these and other processes will be calculated and included in future greenhouse gas emission inventories.

---

[1] Carbon dioxide is also emitted during combustion of biomass fuels (e.g., wood, ethanol, charcoal, bagasse, agricultural wastes, and vegetal fuels such as soybean-based diesel fuel and "black liquor" from wood – a fuel used in paper mills). In the U.S., biomass fuels are generally grown on a sustainable basis. Under the GHG emission estimation guidelines prepared by the Intergovernmental Panel on Climate Change (IPCC), carbon dioxide emissions from biomass fuels grown sustainably are not counted. Therefore, the method described in this chapter does not address biomass fuels as a source of GHGs. For cases where biomass fuels are not grown sustainably, the GHG impact should be captured as a land use change; the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* provides information on how to do so.

3

OVERVIEW OF AVAILABLE METHODS

In general, the basic method for estimating emissions from industrial production and consumption processes is to gather information on the various activity levels required for the calculation (*i.e.*, production and/or consumption data) and then to multiply them by their respective emission coefficients.

$$\text{Activity Level} \times \text{Emissions Factor} = \text{Amount Emitted}$$

In some instances, emission control or recovery technologies have been implemented at facilities which will reduce the amount of gas actually emitted. These avoided emissions should be accounted for by subtracting from emission totals the amount recovered or avoided.

The emission methodologies presented here generally follow the methods developed by the Intergovernmental Panel on Climate Change. (IPCC 1997) For some sources, the IPCC has not provided specific details (*e.g.*, default emission factors) to calculate emissions, but recommends a basic approach that can be followed for each source category (*i.e.*, multiplying production data for each process by an emission factor per unit of

Methods for developing greenhouse gas inventories are continuously evolving and improving. The methods presented in this volume represent the work of the EIIP Greenhouse Gas Committee in 1998 and early 1999. This volume takes into account the guidance and information available at the time on inventory methods, specifically, U.S. EPA's *State Workbook: Methodologies for Estimating Greenhouse Gas Emissions* (U.S.EPA 1998a), volumes 1-3 of the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC, 1997), and the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 1996* (U.S. EPA 1998b).

There have been several recent developments in inventory methodologies, including:

- Publication of EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 1997* (U.S. EPA 1999) and completion of the draft inventory for 1990 – 1998. These documents will include methodological improvements for several sources and present the U.S. methodologies in a more transparent manner than in previous inventories;
- Initiation of several new programs with industry, which provide new data and information that can be applied to current methods or applied to more accurate and reliable methods (so called "higher tier methods" by IPCC); and
- The IPCC Greenhouse Gas Inventory Program's upcoming report on Good Practice in Inventory Management, which develops good practice guidance for the implementation of the 1996 IPCC Guidelines. The report will be published by the IPCC in May 2000.

Note that the EIIP Greenhouse Gas Committee has not incorporated these developments into this version of the volume. Given the rapid pace of change in the area of greenhouse gas inventory methodologies, users of this document are encouraged to seek the most up-to-date information from EPA and the IPCC when developing inventories. EPA intends to provide periodic updates to the EIIP chapters to reflect important methodological developments. To determine whether an updated version of this chapter is available, please check the EIIP site at http://www.epa.gov/ttn/chief/eiip/techrep.htm#green.

production). The methods provided to estimate emissions in this section generally follow this basic approach. The methods provided here are also consistent with the methods used in preparing the U.S. greenhouse gas inventory (U.S. EPA 1999). In some cases, estimation methodologies developed by states have been incorporated as well.

4

PREFERRED METHOD FOR ESTIMATING EMISSIONS

This section presents the preferred method for estimating greenhouse gas emissions from
- Cement production (CO_2)
- Nitric acid production (N_2O)
- Adipic acid production (N_2O)
- Lime manufacture (CO_2)
- Limestone use (CO_2)
- Soda ash manufacture and consumption (CO_2)
- Aluminum production (CO_2)
- Aluminum production (perfluorocarbons)
- HCFC-22 production (HFC-23)
- HFCs and PFCs from consumption of substitutes for ozone-depleting substances (HFCs)
- SF_6 consumption by electric utilities (SF_6)
- Magnesium production (SF_6)
- CO_2 manufacture (CO_2)

Calculations are initially performed to estimate emissions in units of short tons. Section 2-4.14 provides a table to convert the units to metric tons of carbon equivalent.[2]

4.1 CO_2 FROM CEMENT PRODUCTION

Carbon dioxide emitted during the cement production process represents the most significant non-energy source of industrial carbon dioxide emissions. Cement is produced in most states (and in Puerto Rico) and is used in all of them. Carbon dioxide is created when calcium carbonate ($CaCO_3$) is heated in a cement kiln to form lime (calcium oxide or CaO) and carbon dioxide. This process is known as *calcination* or *calcining*:

$$CaCO_3 + Heat \rightarrow CaO + CO_2$$

---
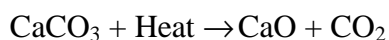
[2] Note that this chapter does not cover emissions from iron and steel production, or from ammonia manufacture. For iron and steel, coke is the primary source of emissions; for ammonia, natural gas feedstocks are the primary source of emissions. In both cases, these emissions should be counted under the chapter 1 methodology for non-fuel uses of fossil fuels. State analysts should review the energy statistics they employ so as not to exclude or double count emissions from these sources.

The lime is then combined with silica-containing materials (provided to the kiln as clays or shales) to form dicalcium or tricalcium silicates, two of the four major compounds in cement clinker, an intermediate product from which finished portland and masonry cement are made (Griffin, 1987), while the carbon dioxide is released into the atmosphere.

Step (1) Obtain Required Data

- *Required Data.* The data needed to calculate CO_2 emissions from cement production in a state are (1) annual clinker production and (2) annual masonry cement production (measured in short tons). Note that for illustrative purposes, national data are presented in the examples; a state should follow the same approach using state data.

- *Data Source.* In-state sources should be consulted first. Additionally, cement production by state can be found in *Cement: Annual Report*, published by the U.S. Geological Survey.[3]

- *Units for Reporting Data.* Annual production of clinker and masonry cement should be supplied in short tons.

Example   According to the Bureau of Mines *Cement Annual Report: 1990* (Bureau of Mines 1992a), total U.S. clinker production in 1990 was **70,939,000 short tons**, and total masonry cement production was **3,208,000 short tons**.

Step (2) Estimate CO_2 Emissions from Clinker Production

Carbon dioxide emissions are estimated based on an emission factor, in tons of CO_2 released per ton of clinker produced. The emission factor recommended for use by states is the product of the fraction of lime used in the cement clinker and a constant reflecting the mass of CO_2 released per unit of lime. The emission factor was calculated as follows:

$$EF_{clinker} = fraction\ CaO \times \left(\frac{44.01\text{g/mole CO}_2}{56.08\text{g/mole CaO}} \right)$$

This analysis assumes an average lime fraction for clinker of 64.6 percent, which yields an emission factor of 0.507 tons of carbon dioxide per ton of clinker produced.

- Multiply clinker production by an emissions factor of 0.507 tons CO_2/ ton of clinker produced to yield total CO_2 emissions from clinker production.

---

[3] The functions of the Department of Interior's Bureau of Mines have been taken over by the Department of Interior's U.S. Geological Survey (USGS). Many of the data sources listed in this workbook were published by the Bureau of Mines; however, current issues of the same publications are available from USGS in Arlington, VA.

Total CO_2 Emissions (tons) $=$ Total Clinker Production (tons) $\times$ 0.507 (tons CO_2/ton of clinker produced)

Example   To calculate Total CO_2 Emissions from U.S. clinker production in 1990:

70,939,000 tons $\times$ 0.507 tons CO_2/ton cement = **35,966,073 tons CO_2**

Step (3) Estimate CO_2 Emissions from Masonry Cement

Masonry cement requires additional lime, over and above the lime used in the clinker. During the production of masonry cement, non-plasticizer additives such as lime, slag, and shale are added to the cement, increasing its weight by 5 percent. Lime accounts for approximately 60 percent of the added substances. An emission factor for this additional lime can be calculated as follows:

$$EF_{mas} = \left(\frac{\text{fraction of weight added}}{1 + \text{fraction of weight added}}\right) \times \left(\begin{array}{c}\text{fraction lime} \\ \text{in added} \\ \text{substance}\end{array}\right) \times \left(\frac{44.01\,\text{g/mole CO}_2}{56.08\,\text{g/mole CaO}}\right)$$

$$= \left(\frac{0.05}{1 + 0.05}\right) \times 0.60 \times 0.785$$

$$= 0.0224$$

Thus, 0.0224 tons of additional carbon dioxide are emitted for every ton of masonry cement produced.

- Multiply masonry cement production by an emissions factor of 0.0224 tons of CO_2/ ton of masonry cement produced

Total CO_2 Emissions (tons) = Total Masonry Cement Production (tons) $\times$ 0.0224 (tons CO_2/ton of masonry cement produced)

Example   To calculate Total CO_2 Emissions from masonry cement production in 1990:

3,208,000 tons $\times$ 0.0224 tons CO_2/ton masonry cement = **71,859 tons CO_2**

Step (4) Sum the Results of Steps (2) and (3)

Total CO_2 emissions from cement production are the sum of the results obtained through Steps (2) and (3). Enter the sum in Table 2.4-1.

> **Example**   To calculate Total CO_2 Emissions from cement production in 1990,
>
> 35,966,073 tons CO_2 (clinker) + 71,859 tons CO_2 (masonry cement) = **36,037,932 tons CO_2**

Some amount of CO_2 is reabsorbed when the cement is used for construction. As cement reacts with water, alkaline substances such as calcium hydroxide are formed. During the curing process, these compounds may react with CO_2 in the atmosphere to create calcium carbonate. This reaction only occurs in roughly the outer 0.2 inches of surface area. Since the amount of CO_2 reabsorbed is thought to be minimal, we have not included a methodology for estimating this amount.

4.2 CO_2 FROM LIME PRODUCTION

Lime is a manufactured product with many chemical, industrial, and environmental uses. In 1990, lime ranked fifth in total production of all chemicals in the United States. Its major uses are in steelmaking, construction, pulp and paper manufacturing, and water and sewage treatment. Lime is manufactured by heating limestone (mostly calcium carbonate – $CaCO_3$) in a kiln, creating calcium oxide (quicklime) and carbon dioxide. The carbon dioxide is driven off as a gas and is normally emitted to the atmosphere.

Step (1) Obtain Required Data

- *Required Data.* The data needed to calculate CO_2 emissions from manufacture of lime (chemical formula: CaO) from limestone ($CaCO_3$) are (1) annual lime production in short tons and (2) the amount of CO_2 recovered during manufacturing and used for other purposes in the state. Data sources for the first data element generally do not include lime manufactured at pulp mills, carbide plants, and water treatment plants. Therefore, where possible, a state should seek additional data that can be used to determine the quantity of lime produced by these other sources. For example, Washington state obtained data on the amount of pulp produced, and used the methodology explained below to estimate CO_2 emissions from lime produced at pulp mills. Note that for illustrative purposes, national data are presented in the examples; a state should follow the same approach using state data.

- *Data Source.* In-state sources such as the state's environmental agency should be consulted first. Additionally, lime production by state can be found in *Lime Annual Report* (U.S. Department of Interior, U.S. Geological Survey); however, this data source does not include lime produced at paper mills, carbide plants, and water treatment plants. Information on state pulp production may be found in the *International Pulp and Paper Directory* (available through Miller Freeman Books, Gilroy, CA).

- *Units for Reporting Data.* Annual production of lime should be supplied in short tons.

Example According to the Bureau of Mines (1992b), total U.S. lime production in 1990 was approximately **17,481 thousand short tons** and **573 thousand tons of CO$_2$** were recovered and used in sugar refining and precipitated calcium carbonate production.

Step (2) Estimate CO$_2$ Emissions from Lime Manufacture

Lime production involves three main processes: stone preparation, calcination, and hydration. Carbon dioxide is generated during the calcination stage, when limestone (calcium carbonate or a combination of calcium and magnesium carbonate) or other calcium carbonate materials are roasted at high temperatures. This process is usually performed in either a rotary or vertical kiln. Carbon dioxide is produced as a by-product of this process, just as CO$_2$ is released during clinker production (see Section 2.1 on cement production). The carbon dioxide is driven off as a gas and normally exits the system with the stack gas. The mass of CO$_2$ released per unit of lime produced can be calculated based on their molecular weights:

$$44.01 \text{ g/mole CO}_2 \div 56.08 \text{ g/mole CaO} = 0.785$$

Therefore, an emissions factor of 0.785 tons of CO$_2$ per ton of lime manufactured is recommended for use by states.

- To determine CO$_2$ emissions from lime manufacture, multiply lime production by an emissions factor[4] of 44 tons CO$_2$/56 tons CaO or 0.785 tons CO$_2$/ton of lime produced. If any CO$_2$ is recovered and used for other purposes, subtract this amount from the total.

CO$_2$ Emissions from Lime Manufacture (tons) = Total Lime Production (tons) × 0.785 (tons CO$_2$/ton of lime produced) - Amount CO$_2$ Recovered (tons)

---

[4] This emission factor assumes that the lime produced is 100 percent pure.

Example To calculate total CO_2 emissions from U.S. lime production in 1990,

[17,481,000 tons $\times$ 0.785 tons CO_2/tons lime] - 573,000 tons CO_2[1] = **13,150,000 tons CO_2**

[1]Some of the CO_2 generated during the production process, however, is recovered for use in sugar refining and precipitated calcium carbonate production. Lime production by these producers was 911 thousand short tons, generating 716.5 thousand short tons of carbon dioxide. Approximately 80 percent of this CO_2 (573,000 tons) is recovered and not emitted.

- If lime production data used above *does not* include lime produced at pulp mills, multiply pulp production at pulp mills that manufacture lime for their own needs by a lime consumption factor of 0.25 tons of lime for each ton of pulp. Multiply the resulting amount of lime used by an emission factor of 0.785 tons CO_2/ton of lime produced to yield CO_2 emissions from lime produced at pulp mills.

CO_2 Emissions from Lime Manufacture at Pulp Mills (tons) = Pulp Production (tons) $\times$ 0.25 tons of Lime Produced/ton Pulp) $\times$ 0.785 (tons CO_2/ton of Lime Produced)

- Add CO_2 emissions from lime manufacture to CO_2 emissions from additional lime manufacture at pulp mills to yield total CO_2 emissions from lime manufacture. Enter the sum in Table 2.4-1.

The term "lime" denotes a variety of chemical and physical forms of this commodity. Uncertainties in emission estimates can be attributed to slight differences in the chemical composition of these products. For example, although much care is taken to avoid contamination during the production process, lime typically contains trace amounts of impurities such as iron oxide, alumina, and silica. Due to differences in the limestone used as a raw material, a rigid specification of lime material is impossible. As a result, few plants manufacture lime with exactly the same properties.

A portion of the carbon dioxide emitted during lime production will actually be reabsorbed when the lime is consumed. In most processes that use lime (*e.g.*, water softening), carbon dioxide reacts with the lime to create calcium carbonate. This is not necessarily true for lime consumption in the steel industry, however, which is the largest lime consumer. A detailed accounting of lime use in the U.S. and further research into the associated processes are required to quantify the amount of carbon dioxide that is reabsorbed.

4.3 CO_2 FROM LIMESTONE USE

Limestone is a basic raw material used by a wide variety of industries, including the construction, agriculture, chemical, and metallurgical industries. For example, limestone can be used as a flux or purifier in refining metals such as iron. In this case, limestone heated in a blast furnace reacts with impurities in the iron ore and fuels, generating carbon dioxide as a by-product. Limestone is also used for glass manufacturing and for SO_2 removal from stack gases in utility and industrial plants.

Step (1) Obtain Required Data

- *Required Data.* The data required are the amounts of each type of limestone consumed in the state for industrial purposes: (1) limestone (calcite), and (2) dolomite. Do not count (1) crushed limestone consumed for road construction or similar uses (because these uses do not result in CO_2 emissions), nor (2) limestone used for agricultural purposes (because agricultural use of limestone will be counted under the methodology presented in Chapter 9), nor (3) limestone used in cement production (because that has been counted above under section 4.1 of this chapter). Note that for illustrative purposes, national data are presented in the examples; a state should follow the same approach using state data.

- *Data Source.* In-state sources should be consulted. State-specific resources and contacts may be found on the World Wide Web at http://minerals.er.usgs.gov/minerals/pubs/state/index.html#contact. Although the federal government makes available data on limestone consumption, these data are not disaggregated to the level of industrial uses by state.

- *Units for Reporting Data.* Annual consumption of limestone and dolomite should be supplied in short tons.

Example   According to the Bureau of Mines (1993b), total U.S. limestone use in 1990 was approximately **12,606,000 short tons**: 11,582,000 short tons limestone (calcite) and 1,024,000 short tons dolomite.

Step (2) Estimate CO_2 Emissions from Limestone Use

Heated limestone generates carbon dioxide as a by-product. Carbon emissions can be calculated by multiplying the amount of limestone consumed by type (*i.e.*, calcite or dolomite) by the carbon content of the limestone. Therefore, emission factors recommended for use by states are 0.12 tons C per ton of limestone (or calcite) consumed and 0.13 tons C per ton of dolomite consumed.[5] Estimates are then multiplied by 44/12 to obtain the amount of carbon emitted as CO_2.

- *Limestone (Calcite)*

  Total CO_2 Emissions (tons) = Limestone Used (tons) $\times$ 0.12 tons C/ton Limestone (Calcite) $\times$ 44/12 CO_2/C.
  b) Dolomite
  Total CO_2 Emissions (tons) = Limestone Used (tons) $\times$ 0.13 tons C/ton Dolomite $\times$ 44/12 CO_2/C.

---

[5] Limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) are collectively referred to as limestone by the industry, and intermediate varieties are seldom distinguished.

Example To calculate Total CO_2 Emissions from lime consumption in 1990,

Calcite

[11,582,000 tons $\times$ 0.12 tons C/ton limestone (calcite)] $\times$ 44/12 CO_2/C = **5,096,000 tons CO_2**

Dolomite

[1,024,000 tons $\times$ 0.13 tons C/ton limestone (dolomite)] $\times$ 44/12 CO_2/C = **488,000 tons CO_2**

Step (3) Sum the Results of Steps 2a and 2b to Obtain Total Emissions

Total CO_2 Emissions from Limestone Use = Total CO_2 from Limestone (Calcite) (tons CO_2) + Total CO_2 from Dolomite (tons CO_2). Enter the sum in Table 2.4-1.

Example To calculate Total CO_2 Emissions from limestone use in 1990,

5,096,000 tons CO_2 limestone (calcite) + 488,000 tons CO_2 (dolomite) = **5,584,000 tons CO_2**

Uncertainties in estimates calculated using this method can be attributed to variations in the chemical composition of limestone. In addition to calcite, limestone may contain smaller amounts of magnesia, silica, and sulfur. The exact specifications for limestone or dolomite used as flux stone vary with the pyrometallurgical process, the kind of ore processed, and the final use of the slag. Similarly, the quality of the limestone used for glass manufacturing will depend on the type of glass being manufactured. Uncertainties also exist in the activity data: much of the limestone consumed in the U.S. is reported as "other unspecified uses."

4.4 CO_2 FROM SODA ASH MANUFACTURE AND CONSUMPTION

Although only two states produce soda ash (Wyoming and California), all states consume it. Thus, all states should estimate the CO_2 emissions from soda ash consumption.

Commercial soda ash (sodium carbonate) is used in many familiar consumer products such as glass, soap and detergents, paper, textiles, and food. About 75 percent of world production is synthetic ash made from sodium chloride; the remaining 25 percent is produced from natural sources. The U.S. produces only natural soda ash, using one of two methods.

Under the soda ash production method used in Wyoming, trona (an ore from which natural soda ash is made) is calcined in a rotary kiln and chemically transformed into a crude soda ash that requires further processing. Carbon dioxide and water are generated as a by-product of the calcination process. CO_2 emissions from the calcination of trona can be estimated based on the following chemical reaction:

$$2(Na_3H(CO_3)_2 \cdot 2H_2O) \rightarrow 3Na_2CO_3 + 5H_2O + CO_2$$
$$\text{[trona]} \qquad\qquad\qquad \text{[soda ash]}$$

Based on this formula, it takes approximately 10.27 tons of trona to generate 1 ton of CO_2, or 0.0974 tons of CO_2 per ton of trona produced.

The soda ash production method used in California uses sodium carbonate-bearing brines. To extract the sodium carbonate, the complex brines are first treated with carbon dioxide in carbonation towers to convert the sodium carbonate into sodium bicarbonate, which precipitates. The precipitated sodium bicarbonate is then calcined back into sodium carbonate. Although CO_2 is generated as a by-product, the CO_2 is recovered and recycled for use in the carbonation stage and is not released. Thus, this process does not result in CO_2 emissions.

Carbon dioxide is also released when soda ash is consumed. Glass manufacture represents about 49 percent of domestic soda ash consumption, with smaller amounts used for chemical manufacture, soap and detergents, flue gas desulfurization, and other miscellaneous uses. In each of these applications, a mole of carbon is released for every mole of soda ash used. Thus, approximately 0.113 tons of carbon or 0.415 tons of CO_2 are released for every ton of soda ash consumed.

Step (1) Obtain Required Data

- *Required Data.* For Wyoming, the data required are the amount of trona (the principal ore from which natural soda ash is made) produced. For all states, the data required are the amount of finished soda ash consumed. Note that for illustrative purposes, national data are presented in the examples; a state should follow the same approach using state data.

- *Data Source.* In-state sources should be consulted first. Additionally, trona production and soda ash consumption by state may be found in *Soda Ash: Annual Report* (U.S. Geological Survey) and *Current Industrial Reports* (Bureau of Census, U.S. Department of Commerce).

- *Units for Reporting Data.* Annual production of trona and consumption of soda ash should be supplied in short tons.

Example   Trona production in Wyoming in 1990 was approximately **16,241,200 short tons**, while total U.S. soda ash consumption in 1990 was **7,194,700 short tons**.

Step (2) Estimate CO$_2$ Emissions from Soda Ash Manufacture (Wyoming Only)

- Multiply the amount of trona produced by the emissions factor 0.0974 tons CO$_2$/ton trona.

    Total CO$_2$ Emissions (tons) = Trona Produced (tons) $\times$ 0.0974 tons CO$_2$/ton Trona.

Example   To calculate CO$_2$ Emissions from trona production in Wyoming in 1990:

16,241,200 tons trona $\times$ 0.0974 tons CO$_2$/ton trona = **1,582,000 tons CO$_2$**

Step (3) Estimate CO$_2$ from Soda Ash Consumption (All States)

- Multiply the amount of soda ash consumed by the emissions factor 0.415 tons CO$_2$/ton soda ash consumed.

    Total CO$_2$ Emissions (tons) = Soda Ash Consumed (tons) $\times$ 0.415 tons CO$_2$/ton Soda Ash

---

Example   To calculate Total U.S. CO$_2$ Emissions from soda ash consumption in 1990,

7,194,700 tons $\times$ 0.415 tons CO$_2$/ton soda ash = **2,986,000 tons CO$_2$**

Step (4) Sum the Results of Steps 2 and 3 to Obtain Total Emissions

Total CO$_2$ Emissions from Soda Ash Manufacture and Use = Total CO$_2$ from Trona Production (tons CO$_2$) + Total CO$_2$ from Soda Ash Consumption (tons CO$_2$). Enter the sum in Table 2.4-1.

4.5   CO$_2$ FROM ALUMINUM PRODUCTION

When aluminum is produced from raw materials, CO$_2$ is emitted in the production process when aluminum oxide is reduced to aluminum. The reduction process takes place in containers with a carbon anode made of petroleum coke. The oxygen in aluminum oxide combines with the carbon in petroleum coke, producing aluminum metal and carbon dioxide (which is emitted as a gas). These emissions do not occur when aluminum is made from recycled aluminum, because there is no reduction process involved.

These carbon dioxide emissions from aluminum manufacture should only be counted if the state's estimate of carbon dioxide emissions from fossil fuel use *does not* include the consumption of petroleum coke in the industrial sector. If the state uses the US DOE Energy

Information Administration's *State Energy Data Report*, the petroleum coke in the aluminum industry (and in other industrial uses) is shown in that report's category "petroleum, other." If the state does <u>not</u> use the data in the "petroleum, other" category (i.e., if the state does not obtain from the Energy Information Administration the state-specific breakdown of types and amounts of fuels in the "petroleum, other" category), then the state should use this section to estimate carbon dioxide emissions from use of petroleum coke in making aluminum from virgin inputs.

Step (1) Obtain Required Data

- *Required Data.* The data element required is the state's production of primary aluminum (i.e., aluminum produced from virgin inputs), in short tons. (When aluminum is produced from recycled inputs there is no reduction process and thus no carbon dioxide emissions from this process.) Note that for illustrative purposes, national data are presented in the examples; a state should follow the same approach using state data.

- *Data Source.* In-state sources should be consulted first. Additionally, primary aluminum production capacity by state can be found in *Aluminum, Bauxite, and Alumina: Annual Report* (U.S. Geological Survey) and *Current Industrial Reports* (Bureau of Census, U.S. Department of Commerce). To estimate production based on production capacity, multiply the state's production capacity by the ratio of national production to national capacity.

Ratio of National Production to National Capacity

Year	1990	1991	1992	1993	1994	1995	1996	1997	1998
Ratio	98.80%	99.71%	97.09%	88.76%	78.92%	80.55%	85.37%	85.79%	88.19%

- *Units for Reporting Data.* Annual production of aluminum from raw materials should be supplied in short tons.

Example   According to the Bureau of Mines (1993a), total U.S. primary aluminum production (i.e., from virgin inputs) in 1990 was approximately **4,462,000 short tons.**

Step (2) Estimate Carbon Dioxide Emissions from Aluminum Production

- Multiply the amount of aluminum produced from raw materials by the emissions factor: 1.5 tons CO_2/ton aluminum produced.[6] Enter the product in Table 2.4-1.

  Total CO_2 Emissions (tons) = [Aluminum Produced from Virgin Inputs (tons) $\times$ 1.5 tons CO_2/ton aluminum produced]

Example   To calculate CO_2 emissions from primary aluminum production in 1990,

[4,462,000 tons $\times$ 1.5 tons CO_2/ton aluminum produced] = **6,690,000 tons CO_2**

4.6   CARBON DIOXIDE MANUFACTURE

Carbon dioxide is used for a variety of industrial and miscellaneous applications, including food processing, chemical production, carbonated beverages, and enhanced oil recovery. Carbon dioxide used for enhanced oil recovery is injected into the ground to increase reservoir pressure, and is therefore considered sequestered.[7] For the most part, however, carbon dioxide used in other applications will eventually enter the atmosphere.

With the exception of a few natural wells, carbon dioxide is produced as a by-product from the production of other chemicals (*e.g.*, ammonia), or obtained by separation from crude oil or natural gas. Depending on the raw materials that are used, the by-product carbon dioxide generated during these production processes may already be accounted for in the CO_2 emission estimates from fossil fuel consumption (either during combustion or from non-fuel use). For example, ammonia is manufactured using natural gas and naphtha as feedstocks. Carbon dioxide emissions from this process are included in the portion of carbon for non-fuel use that is not sequestered (see Chapter 1).

Because (1) carbon dioxide used for enhanced oil recovery is considered sequestered; and (2) carbon dioxide used in chemical production is often manufactured from fossil fuel feedstocks, and thus counted under the methodology in Chapter 1, the major emission sources for manufactured CO_2 that are counted in this step are food processing and carbonated beverages. Because these industries are widespread throughout the U.S., these emissions are estimated by pro-rating national emissions based on state population.

---

[6] This emission factor applies for the prebaked anode plants most commonly used in the U.S.

[7] It is unclear to what extent the CO_2 used for enhanced oil recovery will be re-released. For example, the carbon dioxide used for enhanced oil recovery is likely to show up at the wellhead after a few years of injection (Hangebrauk et al., 1992). This CO_2, however, is typically recovered and reinjected into the well. More research is required to determine the amount of carbon dioxide that may potentially escape. In this estimation method, it is assumed that all of the CO_2 remains sequestered.

Step (1) Obtain Required Data

- *Required Data.* The data elements required are (1) U.S. total CO_2 emissions from CO_2 manufacture, (2) state population, and (3) national population.

- *Data Sources.* U.S. total CO_2 emissions from CO_2 manufacture may be found in the U.S. GHG inventory (U.S. EPA 1998). State and national population data may be found at the web site for the U.S. census: http://www.census.gov/prod/1/pop/p25-1127.pdf. In the version published on this site in late 1998, the table for population by state (by year) was provided on page 17. However, this version provided data only through 1994.

- *Units for Reporting Data.* Because the U.S. GHG inventory reports data in metric tons of carbon equivalent (MTCE), data should be reported in MTCE.

Example   U.S. CO_2 emissions from carbon dioxide manufacture in 1996 were **300,000 MTCE**.

Step (2) Estimate Carbon Dioxide Emissions from Carbon Dioxide Manufacture

- Multiply the U.S. total CO_2 emissions from CO_2 manufacture (in MTCE) by (1) the ratio of state population to national population, (2) (1.1023) (the ratio of short tons to metric tons), and (3) 44/12 (the ratio of the molecular weight of CO_2 to the atomic weight of carbon). Enter the product in Table 2.4-1.

  Total State CO_2 Emissions (MTCE) = Total U.S. CO_2 emissions $\times$ (State Population / National Population) $\times$ 1.1023 $\times$ (44/12)

Example   To estimate CO_2 emissions from CO_2 manufacture in Texas in 1996,

300,000 MTCE $\times$ (18,378,000 people/ 260,341,000 people) $\times$ 1.1023 $\times$ 44/12 = **86,000 short tons of CO_2**

4.7 N_2O FROM NITRIC ACID PRODUCTION

The production of nitric acid (HNO_3) produces nitrous oxide (N_2O) as a by-product, via the oxidation of ammonia. Nitric acid is a raw material used primarily to make synthetic commercial fertilizer. It is also a major component in the production of adipic acid (a feedstock for nylon) and explosives. Relatively small quantities of nitric acid are also employed for stainless steel pickling, metal etching, rocket propellants, and nuclear fuel processing. In 1990, this inorganic chemical ranked thirteenth in total production of all chemicals in the United States. Virtually all

of the nitric acid produced in the U.S. is manufactured by the catalytic oxidation of ammonia (U.S. EPA, 1985). During this reaction, nitrous oxide is formed as a by-product and is released from reactor vents into the atmosphere. While the waste gas stream may be cleaned of other pollutants such as nitrogen dioxide (NO_2), there are currently no control measures aimed at eliminating nitrous oxide (N_2O).

Step (1) Obtain Required Data

- *Required Data.* The information needed to calculate N_2O emissions from nitric acid production is the state's annual nitric acid production. If the state does not have such data, the state may estimate nitric acid production based on national nitric acid production, state nitric acid production capacity, and national nitric acid production capacity.

- *Data Source.* In-state sources should be consulted for the state's annual nitric acid production. (There are no known national data sources that provide, free of charge, state-level data on nitric acid production.) If no in-state sources provide data on nitric acid production, then obtain data on (1) national nitric acid production, (2) state nitric acid production capacity, and (3) national nitric acid production capacity. Data on national nitric acid production may be found in the U.S. greenhouse gas inventory (U.S. EPA 1998) or *Chemical &Engineering News*. Data on national and state nitric acid production may be found in the *Directory of Chemical Producers* (SRI 1996).

- *Units for Reporting Data.* Data should be reported in units of metric tons.

> *Example*   U.S. nitric acid production in 1996 was **8,252,000 metric tons**.

Step (2) Estimate N_2O Emissions from Nitric Acid Production

Off-gas measurements at one nitric acid production facility showed N_2O emission rates to be approximately 0.002 to 0.009 metric tons of N_2O per metric ton of nitric acid produced. It is therefore recommended that states use the midpoint of the range as the emission factor to estimate emissions from this source: 0.0055 metric tons N_2O (i.e., .0061 short tons N_2O) per metric ton of nitric acid produced.

- If you have state data on nitric acid production, multiply nitric acid production by an emissions factor of 0.0061 short tons N_2O/metric ton of nitric acid produced to yield total N_2O emissions from nitric acid production. Enter the product in Table 2.4-1.

- If you do not have state data on nitric acid production, multiply the national nitric acid production for the year in question by the ratio of the state nitric acid capacity to the national nitric acid capacity. This multiplication yields an estimate of state nitric acid production. Then multiply the state's estimated nitric acid production by an emissions

factor of 0.0061 short tons N_2O/metric ton of nitric acid produced to yield total N_2O emissions from nitric acid production. Enter the product in Table 2.4-1.

Total N_2O Emissions (short tons) = Total Nitric Acid Production (metric tons) $\times$ 0.0061 (short tons N_2O/metric ton of nitric acid produced). Enter the product in Table 2.4-1.

Example   To estimate total N_2O emissions from nitric acid production in Nebraska in 1996:

The Nebraska proportion of U.S. nitric acid production capacity in 1996 was (305,000 metric tons/9,795,000 metric tons) = 0.03 = **3 percent**

8,252,000 metric tons $\times$ 3 percent $\times$ 0.0061 short tons N_2O/metric ton nitric acid = **1,500 short tons N_2O**

The emission factors presented are highly uncertain because of insufficient information on manufacturing processes and emission controls. Although no abatement techniques are specifically directed at removing nitrous oxide, existing control measures for other pollutants will have some effect on the nitrous oxide contained in the gas stream. While the emission coefficients presented here do account for these other abatement systems, there may be some variation in abatement levels across different plants.

4.8 N_2O FROM ADIPIC ACID PRODUCTION

As of this writing, three states in the U.S. –Texas, Florida, and Virginia—produce adipic acid. Adipic acid is a white crystalline solid used in the manufacture of synthetic fibers, coatings, plastics, urethane foams, elastomers, and synthetic lubricants. Commercially, it is the most important of the aliphatic dicarboxylic acids, which are used to manufacture polyesters. Ninety percent of all adipic acid produced in the United States is used in the production of nylon 6,6, as well as production of some low-temperature lubricants. It is also used to provide foods with a "tangy" flavor. The U.S. accounts for approximately one-third of global production of adipic acid (Thiemens & Trogler, 1991).

Adipic acid is produced through a two-stage process. The second stage involves the oxidation of ketone-alcohol with nitric acid. Nitrous oxide is generated as a by-product of this reaction and enters the waste gas stream. In the U.S., this waste gas is treated to remove NO_X and other regulated pollutants (and, in some cases, N_2O as well) and is then released into the atmosphere. There are currently four plants in the U.S. that produce adipic acid. In 1998, three of these plants had emission control measures that destroyed about 98 percent of the nitrous oxide before it was released into the atmosphere.

Step (1) Obtain Required Data

- *Required Data.* The information needed to calculate N_2O emissions from adipic acid production is annual adipic acid production in short tons and the effectiveness of pollution control equipment used at production facilities in the state. Note that for illustrative purposes, national data are presented in the examples; a state should follow the same approach using state data.

- *Data Source.* In-state sources should be consulted first. Additionally, adipic acid production *capacity* may be found in *Chemical Market Reporter* (data were last provided in the June 15, 1998 issue and are updated about every three years).

- *Units for Reporting Data.* Annual production of adipic acid should be supplied in short tons. Effectiveness of pollution control equipment can be expressed in short tons removed or in percent removal efficiency.

> *Example*   According to U.S. EPA (1998), total U.S. adipic acid production in 1996 was approximately **920,000 short tons**.
>
> If data are available on N_2O emissions controls, the amount of N_2O reductions should also be recorded.

Step (2) Estimate N_2O Emissions from Adipic Acid Production

Because emissions of N_2O in the U.S. are not currently regulated, very little emissions data exist. However, based on the overall reaction stoichiometry for adipic acid, it is estimated that approximately 0.3 tons of nitrous oxide are generated for every ton of adipic acid produced (Thiemens and Trogler 1991). Because N_2O emissions are controlled in some adipic acid production facilities, the amount of N_2O that is actually released will depend on the level of emission controls in place at a specific production facility.

- Estimate state production of adipic acid by multiplying the state's adipic acid production capacity by the ratio of (total U.S. production)/(total U.S. capacity). As of this writing, Texas had two plants with combined adipic acid production capacity of 1210 million pounds per year; Florida had capacity of 670 million pounds per year; and Virginia had capacity of 50 million pounds per year. Thus the total U.S. capacity, the sum of the state capacities, was 1930 million pounds. U.S. production in 1996 was 1840 million pounds (U.S. EPA 1998). Thus, in 1996, the ratio of (total U.S. production)/(total U.S. capacity) was (1840/1930) or 95 percent. Adipic acid production in Texas would thus be estimated at 1210 million pounds capacity times 95 percent, or 1150 million pounds. To convert to tons, divide by 2000.

- Multiply adipic acid production by an emissions factor of 0.3 tons N_2O/ton of adipic acid produced to yield total N_2O emissions from adipic acid production. Subtract the amount of N_2O that is not released as a result of pollution control equipment. Enter the result in Table 2.4-1.

- Total N_2O Emissions (tons) = Total Adipic Acid Production (tons) × 0.3 (tons N_2O/ton of adipic acid produced) - Amount N_2O not Released as a Result of Pollution Control Equipment.

> ***Example***   To calculate Total N_2O Emissions from U.S. adipic acid production in 1996, 920,000 tons
> × 0.3 tons N_2O/tons adipic acid – tons of N_2O emissions prevented by pollution control
> equipment = **276,000 tons N_2O minus tons N_2O emissions prevented by pollution
> control**

4.9   PERFLUOROCARBONS– CF_4 AND C_2F_6 —FROM ALUMINUM PRODUCTION

The aluminum production industry is thought to be the largest source of two PFCs – CF_4 and C_2F_6. Emissions of these two potent greenhouse gases occur during the reduction of alumina in the primary smelting process.[8] Aluminum is produced by the electrolytic reduction of alumina (Al_2O_3) in the Hall-Heroult reduction process, whereby alumina is dissolved in molten cryolite (Na_3AlF_6), which acts as the electrolyte and is the reaction medium. PFCs are formed during disruptions of the production process known as anode effects, which are characterized by a sharp rise in voltage across the production vessel. The PFCs can be produced through two mechanisms: direct reaction of fluorine with the carbon anode; and electrochemical formation. In both cases the fluorine originates from dissociation of the molten cryolite.

Because CF_4 and C_2F_6 are inert, and therefore pose no health or local environmental problems, there has been little study of the processes by which emissions occur and the factors controlling the magnitude of emissions. In general, however, the magnitude of emissions for a given level of production depends on the frequency and duration of the anode effects during that production period. The more frequent and long-lasting the anode effects, the greater the emissions.

The methodology described below combines production data with empirically determined emissions factors to calculate annual emissions. These emissions factors are based on data provided by the aluminum smelters participating in the EPA Climate Protection Division's Voluntary Aluminum Industrial Partnership (VAIP). VAIP partners provide data on their emission reduction progress to EPA on an annual basis. Using this data, which generally consists of either frequency or duration of anode effects, along with aluminum production estimates, EPA has developed estimates of national PFC emissions from aluminum smelting. The method is based on facility-specific estimates for VAIP partners, and estimates of emissions – based on an average emission factor, in terms of emissions per ton of production – for other facilities.

Because the facility-specific data are confidential, the method below relies on estimating emissions within a state as a function of primary aluminum production. Because actual production may also be regarded as confidential, but capacity is not, the method also provides a basis for estimating state emissions as a function of capacity.

---

[8] Perfluorinated carbons are not emitted during the smelting of recycled aluminum.

Step (1) Obtain Required Data

- *Required Data.* The data element required is the amount of aluminum produced in the state from raw materials, in metric tons. (Aluminum production from recycled inputs does not result in perfluorocarbon emissions.) Note that for illustrative purposes, national data are presented in the examples; a state should follow the same approach using state data.

- *Data Source.* In-state sources should be consulted first. Additionally, primary aluminum production capacity by state can be found in *Minerals Yearbook: Aluminum* (U.S. Geological Survey) and *Current Industrial Reports* (Bureau of Census, U.S. Department of Commerce). To estimate production based on production capacity, multiply the state's production capacity by the ratio of national production to national capacity.

Example   According to the U.S. Geological Survey (1999), total U.S. primary aluminum production in 1998 was approximately 3,713,000 metric tons.

Ratio of National Production to National Capacity

Year	1990	1991	1992	1993	1994	1995	1996	1997	1998
Ratio	98.80%	99.71%	97.09%	88.76%	78.92%	80.55%	85.37%	85.79%	88.19%

- *Units for Reporting Data.* Annual production of aluminum from raw materials should be supplied in metric tons. If the value is in short tons, simply multiply the short tons of aluminum produced by the conversion factor of 0.9072 short tons/metric ton.

Step (2) Estimate Perfluorocarbon Emissions from Aluminum Production

The national average emission factor has declined since 1990, due in large part to the efforts of aluminum companies in the VAIP, as shown below. The emission factors provide the rates for total perfluorocarbon emissions (both CF_4 and C_2F_6) in metric tons of carbon equivalent (MTCE) per metric ton of aluminum produced. The actual calculation of the emissions thus requires only two values, the annual production in metric tons and the emissions factor for that particular year.

Total Perfluorocarbon Emissions (MTCE) = [Aluminum Production for Year A $\times$ Emissions Factor for Year A]

Emissions Factors
(MTCE / Metric Ton of Aluminum Produced)

Year	1990	1991	1992	1993	1994	1995	1996	1997	1998
Emissions Factor	1.28	1.12	1.06	1.02	0.92	0.90	0.94	0.83	0.78

> ***Example***   To calculate total perfluorocarbon emissions (both CF_4 and C_2F_6) from aluminum
> production from virgin inputs in 1998:
>
> [3,713,000 metric tons aluminum produced nationally $\times$ 0.78 MTCE of
> perfluorocarbon$_4$/ton aluminum produced] $= 2,885,000$ MTCE of perfluorocarbon
> emissions

Although this is a relatively well-studied emission category (most of the smelters in the U.S. participate in the VAIP), some uncertainty is introduced in the method by applying a national-scale emission factor and production-capacity ratio to the state level.

4.10 HFC-23 FROM HCFC-22 PRODUCTION

Hydrofluorocarbons (HFCs) are chemicals containing hydrogen, fluorine, and carbon. As some of the primary alternatives to the ozone depleting substances (ODSs) being phased out under the *Montreal Protocol* and subsequent amendments, the use of HFCs is expected to increase in the future. Sources of HFC emissions can be categorized as follows:

- Emissions of HFCs produced as by-products of chemical production processes, and

- Emissions of HFCs used as substitutes for ODSs in refrigeration, foam blowing, solvent, aerosol, and fire extinguishing applications (these are "consumptive" uses of HFCs).

One type of HFC known to be emitted in significant quantities is HFC-23, which is emitted as a by-product of HCFC-22 production. The methodology for estimating these emissions is described below; the methodology for estimating HFCs from consumptive uses appears in Section 4.11.

Step (1) Obtain Required Data

- *Required Data.* The data element required is the amount of HCFC-22 produced in a state.

- *Data Source.* State level information regarding HCFC-22 production is usually considered to be confidential business information by the manufacturers and is unlikely to be available. States may want to contact EPA before contacting in-state manufacturers of HCFC-22. EPA's Climate Protection Division is working to collect information and to improve methods for predicting national emissions from this source. They may be able to provide information or methods useful for calculating state-level emissions. To request information, call the Climate Protection Division at 202-564-9190.

- *Units for Reporting Data.* Annual production of HCFC-22 should be supplied in short tons.

Step (2) Estimate HFC-23 Emissions from HCFC-22 Production

The suggested methodology for estimating emissions from this source is to obtain estimates of HCFC-22 production from in-state chemical manufacturers and multiply this production by 0.02 tons of HFC-23 per ton of HCFC-22 produced. A national emission factor will not reflect plant-to-plant differences, which may be significant, particularly when plants have installed abatement technology. However, further precision may not be necessary for the state inventories. Note that it may be difficult for states to obtain the data required to develop more precise estimates.

Many companies now have empirical measurements of HFC-23 emissions from the production of HCFC-22. Where available, states should use such measurements rather than the emissions factor provided here.

• Multiply the amount of HCFC-22 produced by the appropriate emissions factor: 0.02 tons HFC-23/ton HCFC-22 produced (or 2 percent of total HCFC-22 production). Enter the product in Table 2.4-1.

HCFC-22 Produced (tons) × 0.02 tons HFC-23/ton HCFC-22 produced

= Total HFC-23 Emissions (tons)

Example   To calculate Total HFC Emissions from HCFC-22 production for a state that produced 4 million tons of HCFC-22,

4,000,000 tons HCFC-22 × 0.02 tons HFC/ton HCFC-22 produced = **80,000 tons HFC-23**

4.11 HFCS AND PFCS FROM CONSUMPTION OF SUBSTITUTES FOR OZONE-DEPLETING SUBSTANCES

Hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) are used primarily as alternatives to several classes of ozone-depleting substances (ODSs) that are being phased out under the terms of the *Montreal Protocol* and the Clean Air Act Amendments of 1990. ODSs, which include chlorofluorocarbons (CFCs), halons, carbon tetrachloride, methyl chloroform, and hydrochlorofluorocarbons (HCFCs), are used in a variety of industrial applications including refrigeration and air conditioning equipment, aerosols, solvent cleaning, fire extinguishing, foam blowing, and sterilization. Although their substitutes, HFCs and PFCs, are not harmful to the stratospheric ozone layer, they are powerful greenhouse gases.

The major end-use categories used to characterize ODS-substitute use in the United States are:
- motor vehicle air conditioning,
- commercial and industrial refrigeration and air conditioning,
- residential refrigeration and air conditioning,
- aerosols,
- solvent cleaning,
- fire extinguishing equipment,
- foam production, and
- sterilization.

EPA develops annual estimates of the use and emissions of HFCs and PFCs as ODS substitutes in the United States (e.g., U.S. EPA 1998). Using the EPA method to estimate state-level emissions of HFCs and PFCs used as ODS substitutes would require data that may not be available at that level of disaggregation. Much of the data used for estimating emissions at the national level are from trade associations and industry sources that do not break out the information beyond national totals. However, a rough approximation of state-level emissions of HFCs and PFCs used as ODS substitutes can be calculated using a per capita estimate.

Step (1) Obtain Required Data

- *Required Data.* The data elements required are (1) the national emissions of HFCs and PFCs used as ODS substitutes, and (2) values for the state and national populations.

- *Data Sources.* The national emissions of HFCs and PFCs used as ODS substitutes are reported each year in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* (e.g., U.S. EPA 1999). State and national population data may be found at the web site for the U.S. census: http://www.census.gov/prod/1/pop/p25-1127.pdf. In the version published on this site in late 1998, the table for population by state (by year) was provided on page 17.

- *Units for Reporting Data.* Data on emissions of HFCs and PFCs used as ODS substitutes should be reported in units of metric tons of carbon equivalent (MTCE). Data on state and national populations are reported as the number of persons.

Step (2) Estimate State-Level Emissions Based on National Emissions

State-level emissions of HFCs and PFCs used as ODS substitutes may be estimated by first dividing the national emissions by the national population, to obtain per-capita emissions, and then multiplying per-capita emissions by the state population.

Per-capita emissions = (national emissions) / (national population)
State-level emissions = (per-capita emissions) × (state population)

Example	To calculate per-capita emissions of HFCs and PFCs as ODS substitutes, divide the estimate of U.S. emissions by the value for the US population. In 1996, U.S. emissions were estimated at 9.9 million metric tons of carbon equivalent (MTCE). The 1990 U.S. population was 248,709,873. Thus, the per-capita emissions were approximately:

9.9 million MTCE/248.7 million population = 0.04 MTCE/person.

To calculate Total HFC and PFC Emissions from substitutes for ozone-depleting substances for a state with a population of 5 million people in 1990,

5,000,000 persons $\times$ 0.04 MTCE/person = **200,000 MTCE**

4.12 SF$_6$ EMISSIONS FROM ELECTRIC UTILITIES

(Note: Section 5.1 presents an alternative method for estimating SF$_6$ emissions from this source.)

Sulfur hexafluoride (SF$_6$) is the most potent greenhouse gas, with a global warming potential 23,900 times greater than that of carbon dioxide. SF$_6$ is used in several industries, primarily electric utilities and magnesium metal production. Other uses of SF$_6$ include (1) use as a tracing gas for various atmospheric and oceanic scientific studies, and for laboratory hood testing, (2) use in tandem accelerators, (3) limited use in several consumer products (such as athletic shoes, tennis balls, and automotive shock absorbers) (4) limited use in semiconductor manufacturing. (Note: The semiconductor industry uses several high global warming potential gases (PFCs, NF$_3$, and HFC-23) to a much greater extent than SF$_6$. The EPA's Climate Protection Division is developing methods for predicting emissions attributable to these gases based upon U.S. semiconductor production capacity. They may be able to provide information or methods useful for calculating state-level emissions. To request information, call the Climate Protection Division at 202-564-9190).

The largest use for SF$_6$, both domestically and internationally, is as an electrical insulator in electricity transmission and distribution equipment, such as gas-insulated high-voltage circuit breakers, substations, transformers, and transmission lines. Approximately eighty percent of worldwide use of SF$_6$ is in electrical transmission and distribution systems (Maiss and Brenninkmeijer, 1998). The electric utility industry uses the gas because of its high dielectric strength and arc-quenching abilities. Not all of the electric utilities in the US use SF$_6$; use of the gas is more common in urban areas where the space occupied by electrical distribution and transmission facilities is more valuable.

Data concerning the use and emissions of this chemical are difficult to obtain. SF$_6$ emissions, which result from equipment leaks, are not required to be reported. However, SF$_6$ emissions may be estimated by inferring leakage of SF$_6$ where facilities purchase additional SF$_6$ for equipment that already contains the chemical. This is the approach taken by New Jersey, which identified purchasers of SF$_6$ based on Community Right-to-Know reports, and then surveyed some purchasers to estimate purchases. This section outlines New Jersey's approach. Note that this method does not take into account current work by some utilities to capture and recycle SF$_6$. Neither does it account for destruction of SF$_6$ during use.

Step (1) Obtain Required Data

- *Required Data.* The data required is the amount of SF_6 purchased in a state to replace SF_6 which has leaked.

- *Data Source.* The Community Right-to-Know Survey database can be used to identify facilities with SF_6 on site. Operators of such facilities may be contacted to determine the amount of SF_6 purchased to replace the SF_6 released over the past year. Where data are only available from some firms in an industry (e.g., from only the largest electric utility companies), data may be extrapolated to all state firms in that industry, based on the percentage of total sales represented by the firms providing data.

- *Units for Reporting Data*. The data should be reported in tons of SF_6.

> *Example*   According to an analysis by the New Jersey Department of Environmental Protection, in 1994 facilities in the state purchased **58 short tons of SF_6**.

Step (2) Estimate SF_6 Emissions from SF_6 Leaks

- In New Jersey, the electric utilities that purchased SF_6 in 1994 reported that they used it to replace SF_6 that had leaked from their equipment. Thus, for each ton of SF_6 purchased, New Jersey assumed that one ton of SF_6 had been emitted. Enter the estimated amount emitted in Table 2.4-1.

    Total SF_6 emissions = SF_6 purchased (tons) $\times$ 1 ton SF_6 emitted/ton SF_6 purchased.

> *Example*   To calculate Total SF_6 emissions from facilities in New Jersey that purchased SF_6 in 1994, 58 tons SF_6 purchased $\times$ 1 ton SF_6 emitted/ton SF_6 purchased = **58 tons SF_6**

SF_6 can leak from electrical equipment through seals, especially in older equipment. It is also released when equipment is opened for servicing. Using the method described above to estimate annual SF_6 emissions from the electric utility industry, based on the amount of SF_6 gas purchased, will reflect the amount of SF_6 gas that leaks or is lost during service, but will also reflect any increase in stocks of SF_6 in utility equipment. When electric utility purchasers of SF_6 are surveyed about their purchases, they should be asked what portion of their purchases were to replace SF_6 that has leaked, and what portion represents an increase in their SF_6 stocks. Only the portion used to replace SF_6 that has leaked should be reported.

Several practices can reduce emissions of SF_6 from the electric utility industry, including (1) improved work practices by those servicing and maintaining the equipment, (2) discontinuing the practice of venting to the atmosphere, (3) recycling SF_6 gas, (4) improving monitoring of equipment for leaks and repairing or replacing leaking units, (5) installing new equipment with lower leak rates, and (6) replacing SF_6 with acceptable substitutes.

Uncertainties in estimates calculated using the method above can be attributed to uncertainty about leak rates and increases in SF_6 stocks in the electric utility industry.

4.13 SF$_6$ EMISSIONS FROM MAGNESIUM PRODUCTION AND PROCESSING

(Note: Section 5.2 presents an alternative method for estimating SF_6 emissions from this source.)

Only two facilities—in Utah and Washington—produced magnesium from ore in 1998, and there are no plans for significant expansion of primary production in the United States.[9] Magnesium casting firms are found throughout the United States. Castings and wrought magnesium products accounted for 24 percent of U.S. consumption of primary metal in 1997, according to the U.S. Geological Survey (USGS, 1998).

The magnesium metal production and casting industry uses SF_6 as a cover gas to prevent the violent oxidation of molten magnesium in the presence of air. A gas mixture consisting of carbon dioxide, air, and a small concentration of SF_6 is blown over the molten magnesium metal to induce the formation of a protective crust. Most producers of primary magnesium metal and most magnesium part casters use this technique. Sulfur dioxide was previously used for this process, but SF_6 replaced it due to the numerous health and safety risks associated with sulfur dioxide. (The magnesium recycling industry, for the most part, continues to employ sulfur dioxide as a cover gas.) Because of the high cost of SF_6, firms in the industry are voluntarily seeking to reduce their use of the gas. In addition, control systems that more accurately regulate the concentration and flow rate of SF_6 over the melt could reduce overall gas usage, as could better process enclosures and capture of the gas.

Two methods are proposed to estimate emissions from this source. The first method is based on an assumption that emissions of SF_6 by the magnesium industry in a given year equal the industry's SF_6 consumption in that year. This assumption is likely to be valid given that (1) essentially all SF_6 that is used is emitted, (2) firms generally do not maintain large or varying stocks of the gas, and (3) insignificant quantities of SF_6 are destroyed in the process. To use this method, states must obtain data on SF_6 gas consumption by magnesium production and casting firms in the state. Note that the assumption that all gas used is emitted is based on current industry understanding that the gas does not react or decompose during usage. It is possible that the high temperatures used to keep magnesium in its molten phase would cause some gas degradation.

---

[9] Demand for magnesium metal for die-casting, however, has the potential to expand if auto manufacturers design future vehicle models with more magnesium parts.

The second method employs emission factors and activity data for magnesium metal production and casting. States are likely to be able to obtain such activity data more easily than SF_6 consumption data. Regarding emission factors, the Norwegian Institute for Air Research (NIAR 1993) has measured emission factors for primary magnesium production ranging from 1 to 5 kg of SF_6 per metric ton of magnesium. It is believed that most plants in the United States have SF_6 emissions at the low end of this range. A survey of magnesium die casters has reported an emission factor of 4.1 kg of SF_6 per metric ton of magnesium parts die cast (Gjestland and Magers 1996).

Step (1) Obtain Required Data

- *Required Data.* Data are required for either (1) the amount of SF_6 purchased in a state for magnesium production and casting or (2) the amount of magnesium metal produced in the state and the amount of magnesium metal cast in the state.

- *Data Sources.* In-state sources should be consulted first. State-specific resources and contacts for magnesium metal production and casting may be found on the Internet at http://minerals.er.usgs.gov/minerals/pubs/state/index.html#contact. Although the USGS makes available data on magnesium production and casting on the Internet at http://minerals.er.usgs.gov/minerals/pubs/commodity/magnesium/, these data are not disaggregated by state. In the case that these data are not publicly available, the EPA's Climate Protection Division may be contacted at 202-564-9190. The Climate Protection Division is working to collect information and to improve methods for predicting national emissions from this source. They may be able to provide information or methods useful for calculating state-level emissions.

- *Units for Reporting Data*. Data should be reported in tons.

Example   A hypothetical state's magnesium industry might use SF_6 in a given year in the amount of **120 tons**.

Example   A hypothetical state might, in a given year, produce magnesium in the amount of **80,000 tons** and cast magnesium in the amount of **10,000 tons**.

Step (2a) Estimate SF$_6$ Emissions Using SF$_6$ Consumption Data

Note that Steps 2a and 2b tends to overestimate emissions from magnesium manufacture and casting since they do not account for gas returned to the supplier.

- Total SF_6 emissions = SF_6 purchased (metric tons) $\times$ 1 ton SF_6 emitted/ton SF_6 purchased

---

> *Example* To calculate SF_6 emissions by the hypothetical state's magnesium industry,
>
> 120 tons SF_6 used $\times$ 1 ton SF_6 emissions per ton of SF_6 used = **120 tons** SF_6 emissions

---

Step (2b) Estimate SF_6 Emissions Using Magnesium Production and Casting Data

- Total SF_6 emissions = Primary magnesium production (tons) $\times$ 0.001 ton SF_6 emitted/ton magnesium produced + Magnesium casting (tons) $\times$ 0.0041 ton SF_6 emitted/ton magnesium cast

---

> *Example* To calculate SF_6 emissions by the hypothetical state's magnesium industry,
>
> 80,000 tons magnesium produced $\times$ 0.001 ton SF_6 per ton
> + 10,000 tons magnesium cast $\times$ 0.0041 tons SF_6 per ton = **121 tons** SF_6 emissions

---

4.14 SUMMARY TABLE AND CONVERSION OF VALUES TO UNITS OF METRIC TONS OF CARBON EQUIVALENT

The following table is provided to facilitate summing emissions of each gas from the various sectors, and converting the emissions to units of metric tons of carbon equivalent. To perform the conversion, follow the calculations shown in the second to last column. These calculations (1) convert the units from tons to metric tons, using a factor of 0.9072, and (2) convert metric tons to metric tons of carbon equivalent, using factors of (a) 12/44—the mass ratio of carbon to carbon dioxide, and (b) the global warming potential of the gas, which is different for each gas.

Table 2.4-1. Summary Table of Greenhouse Gas Emissions from Production and Consumption Processes, and Conversion of Values to Units of Metric Tons of Carbon Equivalent (MTCE)

Section	Process	Emissions (tons)	Formula to Convert Emissions from Units of Tons to Units of MTCE	Emissions (MTCE)
4.1	CO_2 from cement production			
4.2	CO_2 from lime manufacture			
4.3	CO_2 from limestone use			
4.4	CO_2 from soda ash manufacture and consumption			
4.5	CO_2 from aluminum production			
4.6	CO_2 from carbon dioxide manufacture			
	Total CO_2		=tons $CO_2 \times 0.9072 \times 12/44 \times 1$	
4.7	N_2O from nitric acid production			
4.8	N_2O from adipic acid production			
	Total N_2O		=tons $N_2O \times 0.9072 \times 12/44 \times 310$	
4.9	CF_4 and C_2F_6 from aluminum production		Emissions are already reported in units of MTCE; no conversion is needed.	
4.10	HFC-23 from HCFC-22 production		= tons HFC-23 $\times 0.9072 \times 12/44 \times 11,700$	
4.11	HFCs and PFCs from consumption of substitutes for ozone-depleting substances		Emissions are already reported in units of MTCE; no conversion is needed.	
4.12	SF_6 from electric utilities			
4.13	SF_6 from magnesium production and casting			
	Total SF_6		= tons $SF_6 \times 0.9072 \times 12/44 \times 23,900$	

5

ALTERNATE METHODS FOR ESTIMATING EMISSIONS

The Greenhouse Gas Committee of the Emission Inventory Improvement Program has approved two alternative methods, for estimating SF_6 emissions from electric utilities and from magnesium production and procession. Each method is based on pro-rating national emissions. These methods may be used if state-level data for these sources are not available.

5.1 SF_6 EMISSIONS FROM ELECTRIC UTILITIES

Background information on SF_6 and the preferred method of estimating SF_6 emissions from electric utilities may be found in section 4.11. This alternative method estimates these emissions by pro-rating national emissions, based on the ratio of state electricity consumption to national electricity consumption. Electricity consumption is used to pro-rate national emissions because utility SF_6 emissions result from leaks in the transformers used in the electricity distribution system, and electricity consumption is the best available proxy for calculating a state's share of national SF_6 leaks from transformers.

Step (1) Obtain Required Data

- *Required Data.* The data required are (1) total national emissions of SF_6 from the electric utility sector, (2) the state's electricity consumption, and (3) national electricity consumption.

- *Data Sources.* The national SF_6 emissions from the electric utility sector may be found in the U.S. GHG inventory (U.S. EPA 1998). State and national electricity consumption may be found in the U.S. Department of Energy, Energy Information Administration report, *Electric Power Annual 1997 Vol. II* (U.S. DOE 1998). (In this most recent edition, electricity consumption data may be found on page 26, table 4.)

- *Units for Reporting Data.* Because the U.S. GHG inventory reports data in metric tons of carbon equivalent (MTCE), and the data in Table 2.4-1 are ultimately reported in these units, data should be reported in MTCE.

Step (2) Estimate SF$_6$ Emissions from Electricity Consumption

- Total state SF$_6$ emissions = National SF$_6$ emissions (MTCE) × (state electricity consumption/national electricity consumption). Enter the product in the last column of Table 2.4-1.

> *Example*   To calculate SF$_6$ emissions from electric utilities for New Jersey in 1996:
>
> 7.0 million MTCE SF$_6$ national emissions × (66,889 million kWh consumed by New Jersey/3,097,810 million kWh consumed nationally) = **150,000 MTCE SF$_6$**

5.2   SF$_6$ EMISSIONS FROM MAGNESIUM PRODUCTION AND PROCESSING

Background information on SF$_6$ and the preferred method of estimating SF$_6$ emissions from magnesium production and processing may be found in section 4.13. This alternative method estimates these emissions by pro-rating national emissions for production and processing. National production emissions are pro-rated based on the ratio of state production capacity to national production capacity. National processing emissions are pro-rated based on the ratio of state population to national population. Population data are used to develop the latter estimate because data on magnesium processing capacity by state are not available.

Step (1) Obtain Required Data

- *Required Data.* The required data are (1) national primary production of magnesium, (2) state capacity for magnesium production, (3) national capacity for magnesium production, (4) total national emissions of SF$_6$ from magnesium production and processing, (5) state population, and (6) national population.

- *Data Sources.* Information on national primary production of magnesium as well as state and national magnesium production capacity may be found on the Internet at the following site: http://minerals.er.usgs.gov/minerals/pubs/commodity/magnesium/. The appropriate reference at this site is the Minerals Yearbook and the information can be found in the tables at the back of the document. National SF$_6$ emissions may be found in the U.S. GHG inventory (U.S. EPA 1998). National and state population data can be found on the internet at the following site: http://www.census.gov/prod/1/pop/p25-1127.pdf. This document provides state and national population data estimates through 1994.

- *Units for Reporting Data*. Data on magnesium production and magnesium production capacity should be reported in metric tons. Data on SF$_6$ emissions from magnesium production and processing should be reported in MTCE. Population should be reported in number of persons.

Step (2) Estimate SF$_6$ Emissions from Magnesium Production

- State SF$_6$ emissions from magnesium production in MTCE = national primary production of magnesium in metric tons $\times$ (state magnesium production capacity/national magnesium production capacity) $\times$ (1.1023 tons magnesium/metric ton magnesium) $\times$ (0.001 ton SF$_6$ emitted/ton magnesium produced) $\times$ (12/44) $\times$ 23,900.

Example   To calculate 1996 SF$_6$ emissions from magnesium production for Texas:

National primary magnesium production of 125,000 metric tons $\times$ (65,000 metric tons Texas magnesium production capacity/ 145,000 metric tons national magnesium production capacity) $\times$ (1.1023 tons magnesium/metric ton magnesium) $\times$ (0.001 ton SF$_6$ emitted/ton magnesium produced) $\times$ (12/44) $\times$ 23,900 = **400,000 MTCE SF$_6$**

Step (3) Estimate SF$_6$ Emissions from Magnesium Processing

- First estimate national SF$_6$ emissions from magnesium processing. National SF$_6$ emissions from magnesium processing in MTCE = national SF$_6$ emissions from magnesium production and processing in MTCE - [national primary production of magnesium in metric tons $\times$ (1.1023 tons magnesium/metric ton magnesium) $\times$ (0.001 ton SF$_6$ emitted/ton magnesium produced) $\times$ (12/44) $\times$ 23,900].

Example   To calculate 1996 national SF$_6$ emissions from magnesium processing:

3 million MTCE national SF$_6$ emissions from magnesium production and processing – [national primary magnesium production of 125,000 metric tons $\times$ (1.1023 tons magnesium/metric ton magnesium) $\times$ (0.001 ton SF$_6$ emitted/ton magnesium produced)] = 3 million MTCE – 0.9 million MTCE = **2.1 million MTCE SF$_6$**

- Next estimate state SF$_6$ emissions from magnesium processing. State SF$_6$ emissions from magnesium processing = national SF$_6$ emissions from magnesium processing $\times$ (state population/national population).

Example   To calculate Texas SF$_6$ emissions from magnesium processing:

2.1 million MTCE national SF$_6$ emissions from magnesium processing $\times$ (18,378,000 people/260,341,000 people) = 0.15 million = **150,000 MTCE SF$_6$**

Step (4) Estimate Total SF$_6$ Emissions from Magnesium Production and Processing

- State SF$_6$ emissions from magnesium production and processing in MTCE = State SF$_6$ emissions from magnesium production in MTCE + state SF$_6$ emissions from magnesium processing in MTCE. Enter this amount in the final column of the appropriate row of Table 2.4-1.

> ***Example*** To estimate Texas SF$_6$ emissions from magnesium production and processing:
>
> 400,000 MTCE SF$_6$ + 150,000 MTCE SF$_6$ = 550,000 MTCE SF$_6$

6

QUALITY ASSURANCE/QUALITY CONTROL

Quality assurance (QA) and quality control (QC) are essential elements in producing high quality emission estimates and should be included in all methods to estimate emissions. QA/QC of emissions estimates are accomplished through a set of procedures that ensure the quality and reliability of data collection and processing. These procedures include the use of appropriate emission estimation methods, reasonable assumptions, data reliability checks, and accuracy/logic checks of calculations. Volume VI of this series, *Quality Assurance Procedures*, describes methods and tools for performing these procedures.

Uncertainties in the estimation methods for the various emission sources are discussed above throughout section 4.

6.1   DATA ATTRIBUTE RANKING SYSTEM (DARS) SCORES

DARS is a system for evaluating the quality of data used in an emission inventory. To develop a DARS score, one must evaluate the reliability of eight components of the emissions estimate. Four of the components are related to the activity level (e.g., the tons of clinker produced). The other four components are related to the emission factor (e.g., the amount of CO_2 emitted per ton of clinker produced). For both the activity level and the emission factor, the four attributes evaluated are the measurement method, source specificity, spatial congruity, and temporal congruity. Each component is scored on a scale of zero to one, where one represents a high level of reliability. To derive the DARS score for a given estimation method, the activity level score is multiplied by the emission factor score for each of the four attributes, and the resulting products are averaged. The highest possible DARS composite score is one. A complete discussion of DARS may be found in Chapter 4 of Volume VI, *Quality Assurance Procedures*.

The DARS scores provided here are based on the use of the emission factors provided in this chapter, and activity data from the sources referenced in the various steps of the methodology. Note that some of the sources referenced in this chapter provide data only for certain states. For example, to preserve confidentiality, some data sources may provide data only for states where several producers are located, and thus where data may be aggregated across several producers. States with only one or a few producers may be omitted from the database, or the data from several of those states may be combined. In such cases it may be necessary to use state data sources for activity data. If a state uses state data sources, the state may wish to develop a DARS score based on the use of state data.

TABLE 2.6-1

DARS SCORES: CO$_2$ EMISSIONS FROM CEMENT PRODUCTION

DARS Attribute Category	Emission Factor Attribute	Explanation	Activity Data Attribute	Explanation	Emission Score
Measurement	9	Because the emission factor is not based on measurement, the highest possible score is 5. However, the emission factor is based on a precise stoichiometric relationship.	9	Data on clinker and cement production (from which CO$_2$ is emitted as a by-product) are aggregated from intermittent measurements.	0.81
Source Specificity	10	The emission factor was developed specifically for the intended emission source.	10	The activity measured (clinker and cement production) is the activity from which CO$_2$ is emitted.	1.00
Spatial Congruity	9	The emission factor was developed for a region larger than the one it is applied to; it is not based on state-level production and emissions. However, spatial variability for the emissions factor is assumed to be low.	10	States use state-level activity data to estimate statewide emissions.	0.90
Temporal Congruity	9	The emission factor is based on mass balance, not on measured emissions over a particular time frame. However, the emission factor should not vary significantly over the course of a year.	10	States use annual activity data to estimate annual emissions.	0.90
				Composite Score	**0.90**

TABLE 2.6-2

DARS SCORES: CO$_2$ EMISSIONS FROM LIME PRODUCTION

DARS Attribute Category	Emission Factor Attribute	Explanation	Activity Data Attribute	Explanation	Emission Score
Measurement	8	Because the emission factor is not based on measurement, the highest possible score is 5. The emission factor is based on a precise stoichiometric relationship. Applying the DARS formula, the score would be 5. However, the relationship is precise, although some carbon dioxide is reabsorbed when lime is used for certain purposes.	9	Data on lime production (from which CO$_2$ is emitted as a by-product) are aggregated from intermittent measurements.	0.72
Source Specificity	7	Although the emission factor was developed specifically for the intended emission source, the data source does not account for all lime production. Thus, the emission factor is based on a subset of emission sources. Variability in emissions across sources is assumed to be low to moderate.	9	The data source for the activity measured (lime production) does not account for all lime production. Assuming the lime production activity reported is very closely correlated to all lime production activity, the highest score possible is 9.	0.63
Spatial Congruity	9	The emission factor was developed for a region larger than the one it is applied to; it is not based on state-level production and emissions. However, spatial variability for the emissions factor is assumed to be low.	10	States use state-level activity data to estimate statewide emissions.	0.90
Temporal Congruity	7	The emission factor is based on mass balance, not on measured emissions over a particular time frame. The use of pollution control equipment introduces additional variability, assumed to be low to moderate.	10	States use annual activity data to estimate annual emissions.	0.70
				Composite Score	**0.74**

TABLE 2.6-3

DARS SCORES: CO$_2$ EMISSIONS FROM LIMESTONE USE

DARS Attribute Category	Emission Factor Attribute	Explanation	Activity Data Attribute	Explanation	Emission Score
Measurement	8	Because the emission factor is not based on measurement, the highest possible score is 5. The emission factor is based on a precise stoichiometric relationship. Applying the DARS formula, the score would be 5. However, the relationship is precise, although some carbon may not be released as CO2 when lime is used for certain purposes.	6	Data for limestone consumption (from which CO$_2$ is emitted as a by-product) are based on a proxy (limestone sales).	0.48
Source Specificity	10	The emission factor was developed specifically for the intended emission source.	10	Limestone consumption - the activity measured with a proxy - is the activity from which CO$_2$ is emitted.	1.00
Spatial Congruity	9	The emission factor was developed for a region larger than the one it is applied to; it is not based on state-level production and emissions. However, spatial variability for the emissions factor is assumed to be low.	3	States may need to estimate the state-level activity data based on national-level data; in that case, spatial variability is expected to be high.	0.27
Temporal Congruity	9	The emission factor is based on stoichiometry, not on measured emissions over a particular time frame. However, the emission factor should not vary significantly over the course of a year.	10	States use annual activity data to estimate annual emissions.	0.90
				Composite Score	**0.66**

TABLE 2.6-4

DARS SCORES: CO$_2$ EMISSIONS FROM SODA ASH MANUFACTURE AND CONSUMPTION

DARS Attribute Category	Emission Factor Attribute	Explanation	Activity Data Attribute	Explanation	Emission Score
Measurement	5	Because the emission factors are not based on measurement, the highest possible score is 5. The emission factors are based on a stoichiometric relationship. Applying the DARS formula, the score would be 5. However, the relationship is precise, although CO2 emissions from consumption are less for some uses.	7.5	Data on soda ash manufacture are aggregated from intermittent measurements, suggesting a score of 9. Data for soda ash consumption are based on a proxy (sales), suggesting a score of 6. The composite score is 7.5.	0.38
Source Specificity	10	The emission factor was developed specifically for the intended emission source.	10	The activities measured (either directly or by proxy) are the activities from which CO$_2$ is emitted.	1.00
Spatial Congruity	9	The emission factor was developed for a region larger than the one it is applied to; it is not based on state-level production and emissions. However, spatial variability for the emissions factor is assumed to be low.	10	States use state-level activity data to estimate statewide emissions.	0.90
Temporal Congruity	9	The emission factor is based on mass balance, not on measured emissions over a particular time frame. However, the emission factor should not vary significantly over the course of a year.	10	States use annual activity data to estimate annual emissions.	0.90
				Composite Score	**0.79**

TABLE 2.6-5

DARS SCORES: CO$_2$ EMISSIONS FROM ALUMINUM PRODUCTION

DARS Attribute Category	Emission Factor Attribute	Explanation	Activity Data Attribute	Explanation	Emission Score
Measurement	4	Because the emission factor is not based on measurement, the highest possible score is 5. The emission factor is based on mass balance. Applying the DARS formula, it would get this score, but there is variability in the emission factor across different smelter technologies.	4	Aluminum production activity data are derived from state data on primary aluminum production capacity (based on a scaling factor), not from direct continuous or direct intermittent measurement.	0.16
Source Specificity	10	The emission factor was developed specifically for the intended emission source.	7	Production capacity is measured, not aluminum production. It is assumed that capacity is highly correlated to aluminum production.	0.70
Spatial Congruity	9	The emission factor was developed for a region larger than the one it is applied to; it is not based on state-level production and emissions. However, spatial variability for the emissions factor is assumed to be low.	7	Statewide production is estimated based on state-level production capacity, which is then scaled based on national production and national production capacity. Variability in the capacity utilization among states is assumed to be low to moderate.	0.63
Temporal Congruity	9	The emission factor is based on mass balance, not on measured emissions over a particular time frame. However, the emission factor should not vary significantly over the course of a year.	10	States use annual activity data to estimate annual emissions.	0.90
			Composite Score		**0.60**

TABLE 2.6-6

DARS SCORES: CO₂ EMISSIONS FROM CARBON DIOXIDE MANUFACTURE

DARS Attribute Category	Emission Factor Attribute	Explanation	Activity Data Attribute	Explanation	Emission Score
Measurement	3	The U.S. GHG inventory emission factor (CO2 emitted equals 20 percent of CO2 consumed for uses other than enhanced oil recovery) is based on an estimate by the Freedonia Group that 20 percent of CO2 is produced from natural wells.	3	The Freedonia Group's method for determining U.S. CO2 consumption is not described in the U.S. GHG inventory.	0.09
Source Specificity	10	The emission factor was developed specifically for the intended source category.	5	State population is somewhat correlated to the emission process.	0.50
Spatial Congruity	7	The emission factor was developed for the U.S. as a whole; spatial variability is expected to be moderate.	10	States use state population data to estimate state emissions.	0.70
Temporal Congruity	10	The emission factor was developed to estimate annual emissions.	8	States may use population data from the Census Bureau's most recent census data; temporal variability is expected to be low.	0.80
				Composite Score	0.52

TABLE 2.6-7

DARS SCORES: N$_2$O EMISSIONS FROM NITRIC ACID PRODUCTION

DARS Attribute Category	Emission Factor Attribute	Explanation	Activity Data Attribute	Explanation	Emission Score
Measurement	3	Because the emission factor is based on measurement, the lowest possible score is 5. However, the measurement was from a single plant, and a large range in emissions was measured at that plant.	9	Data on nitric acid production (from which N$_2$O is emitted as a by-product) are aggregated from intermittent measurements.	0.27
Source Specificity	10	The emission factor was developed specifically for the intended emission source.	10	The activity measured (nitric acid production), is the activity from which N$_2$O is emitted.	1.00
Spatial Congruity	9	The emission factor was developed for a region larger than the one it is applied to; it is not based on state-level production and emissions. However, spatial variability for the emissions factor is assumed to be low.	10	States use state-level activity data to estimate statewide emissions.	0.90
Temporal Congruity	9	Because the emission factor is based on mass balance, not on measured emissions over a particular time frame. However, the emission factor should not vary significantly over the course of a year.	10	States use annual activity data to estimate annual emissions.	0.90
				Composite Score	**0.77**

TABLE 2.6-8

DARS SCORES: N$_2$O EMISSIONS FROM ADIPIC ACID PRODUCTION

DARS Attribute Category	Emission Factor Attribute	Explanation	Activity Data Attribute	Explanation	Emission Score
Measurement	4	Because the emission factor is not based on measurement, the highest possible score is 5. The emission factor is based on a stoichiometric relationship developed from a laboratory experiment simulating industrial conditions, but does not account for emission controls at some facilities.	6	Adipic acid production is estimated based on state production capacity and national capacity utilization.	0.24
Source Specificity	10	The emission factor was developed specifically for the intended emission source.	10	The activity measured (adipic acid production) is the activity from which N$_2$O is emitted.	1.00
Spatial Congruity	8	Because the emission factor is based on mass balance, the highest possible score is 9. The use of pollution control equipment introduces variability assumed to be low to moderate.	10	States use state-level activity data to estimate statewide emissions.	0.80
Temporal Congruity	8	The emission factor is based on mass balance, not on measured emissions over a particular time frame. Variability is assumed to be low.	10	States use annual activity data to estimate annual emissions.	0.80
				Composite Score	**0.71**

TABLE 2.6-9

DARS SCORES: CF$_4$ AND C$_2$F$_6$ EMISSIONS FROM ALUMINUM PRODUCTION

DARS Attribute Category	Emission Factor Attribute	Explanation	Activity Data Attribute	Explanation	Emission Score
Measurement	5	The emission factor is based on a relatively small set of measurements, covering some of the range of conditions leading to formation of PFCs.	4	Aluminum production activity data are derived from state data on primary aluminum production capacity (based on a scaling factor), not from direct continuous or direct intermittent measurement.	0.20
Source Specificity	10	The emission factor was developed specifically for the intended emission source.	7	Production capacity is measured, not aluminum production. It is assumed that capacity is highly correlated to aluminum production.	0.70
Spatial Congruity	7	The emission factor was developed for a region larger than the one it is applied to; it is not based on state-level production and emissions. Spatial variability for the emissions factor is assumed to be moderate.	7	Statewide production is estimated based on state-level production capacity, which is then scaled based on national production and national production capacity. Variability in the capacity utilization among states is assumed to be low to moderate.	0.49
Temporal Congruity	7	The temporal variability is expected to be moderate.	10	States use annual activity data to estimate annual emissions.	0.70
				Composite Score	**0.52**

TABLE 2.6-10

DARS SCORES: HFC-23 FROM HCFC-22 PRODUCTION

DARS Attribute Category	Emission Factor Attribute	Explanation	Activity Data Attribute	Explanation	Emission Score
Measurement	8	The emission factor is based on measurement of a representative sample over typical loads.	5	Data on HCFC-22 production (from which HFC-23 is emitted as a by-product) are expected to be obtained by surveying manufacturers, who may provide only rough estimates.	0.40
Source Specificity	10	The emission factor was developed specifically for the intended emission source.	10	The activity measured (HCFC-22 production) is the activity that results in HFC-23 emissions.	1.00
Spatial Congruity	9	The emission factor was developed for a region larger than the one it is applied to; it is not based on state-level production and emissions. However, spatial variability for the emissions factor is assumed to be low.	10	States use state-level activity data to estimate statewide emissions.	0.90
Temporal Congruity	9	The emission factor is based on mass balance, not on measured emissions over a particular time frame. However, the emission factor should not vary significantly over the course of a year.	10	States use annual activity data to estimate annual emissions.	0.90
				Composite Score	**0.80**

TABLE 2.6-11

DARS SCORES: HFCs AND PFCs FROM CONSUMPTION OF SUBSTITUTES FOR OZONE-DEPLETING SUBSTANCES

DARS Attribute Category	Emission Factor Attribute	Explanation	Activity Data Attribute	Explanation	Emission Score
Measurement	3	National vintaging model estimate is based on a crude mass balance approach that estimates leak rates for equipment containing ODS substitutes, and release profiles for such uses as solvents and sterilants.	3	Per-capita national estimate (based on a vintaging model) and state population are used to estimate state emissions.	0.09
Source Specificity	10	The emission factor was developed specifically for the intended source category.	5	State population is somewhat correlated to the emission process.	0.50
Spatial Congruity	9	The emission factor was developed for the U.S. as a whole; spatial variability is expected to be low.	5	States use state population data and national consumption data to estimate state emissions; spatial variability is expected to be moderate to high.	0.45
Temporal Congruity	10	The emission factor was developed to estimate annual emissions.	8	States may use population data from the Census Bureau's most recent census data; temporal variability is expected to be low.	0.80
				Composite Score	**0.46**

TABLE 2.6-12

**DARS SCORES: EMISSIONS OF SF$_6$ FROM ELECTRIC UTILITIES
(PREFERRED METHOD)**

DARS Attribute Category	Emission Factor Attribute	Explanation	Activity Data Attribute	Explanation	Emission Score
Measurement	3	The emission factor was developed via a crude mass balance.	4	SF$_6$ activity data are derived from sales data, not from direct continuous or direct intermittent measurement. Sales data are incomplete, and do not account for all uses, or for changes in inventory and storage.	0.12
Source Specificity	7	Although the emission factor was developed specifically for the intended emission source, data may not be available for all uses. Thus, the emission factor is based on a subset of the emission sources. Variability across sources is assumed to be low to moderate.	3	Activity data are based on sales; sales are a proxy for consumption. On that basis, the score would be 5, but activity data do not account for all uses.	0.21
Spatial Congruity	9	The emission factor was developed for a region larger than the one it is applied to; it is not based on state-level production and emissions. However, spatial variability for the emissions factor is assumed to be low.	10	States use state-level activity data to estimate statewide emissions.	0.90
Temporal Congruity	4	The emission factor is based on mass balance, not on measured emissions over a particular time frame. Applying the DARS formula, and assuming emission factor does not vary significantly over the course of a year, the score would be 9, but emissions in a given year are poorly correlated with sales for that year.	10	States use annual activity data to estimate annual emissions.	0.40
				Composite Score	**0.41**

TABLE 2.6-13

DARS SCORES: EMISSIONS OF SF$_6$ FROM MAGNESIUM PRODUCTION AND CASTING

DARS Attribute Category	Emission Factor Attribute	Explanation	Activity Data Attribute	Explanation	Emission Score
Measurement	4	The Norwegian Institute for Air Research measured emissions from magnesium production and developed a range of emission factors; this method uses the low end of that range. The emission factor for magnesium casting is based on a survey.	9	Data on magnesium production and casting are aggregated from intermittent measurements.	0.36
Source Specificity	10	The emission factors were developed specifically for the intended source.	5	Magnesium production and casting levels are somewhat correlated to emission levels.	0.50
Spatial Congruity	5	The emission factor for magnesium production was developed for Norway, and factor spatial variability was found to be moderate to high. The emission factor for magnesium casting is based on a survey in Europe, North America and Asia; factor spatial variability is unknown.	3	States may need to estimate the state-level activity data based on national-level data; in that case, spatial variability is expected to be high.	0.15
Temporal Congruity	9	The emission factors are not expected to vary significantly over the course of a year.	10	States use annual activity data to estimate annual emissions.	0.90
				Composite Score	**0.48**

*This DARS table is for the estimation method based on magnesium production and casting data. If using the method based on SF6 consumption, the DARS scores and explanations are the same as in Table 2.6-11.

TABLE 2.6-14

DARS SCORES: EMISSIONS OF SF$_6$ FROM ELECTRIC UTILITIES (ALTERNATE METHOD)

DARS Attribute Category	Emission Factor Attribute	Explanation	Activity Data Attribute	Explanation	Emission Score
Measurement	5	The emission factor used in the U.S. greenhouse gas inventory, to estimate U.S. emissions from this sector, was based on mass balance.	6	Electricity consumption is used as a proxy for the number of transformers from which SF6 would leak.	0.30
Source Specificity	7	The emission factor was based on atmospheric concentrations of SF6, as emitted from all sources. Expected variability is low to moderate.	5	Electricity consumption is somewhat correlated to the emissions process.	0.35
Spatial Congruity	7	The emission factor was developed based on global emissions, not U.S. emissions. Spatial variability is expected to be moderate.	10	States use state data on electricity consumption to estimate state emissions.	0.70
Temporal Congruity	7	The emission factor was based on total emissions since 1950; temporal variability is expected to be low to moderate.	10	States use annual data on electricity consumption to estimate annual emissions.	0.70
			Composite Score		0.51

TABLE 2.6-15

DARS SCORES: EMISSIONS OF SF$_6$ FROM MAGNESIUM PRODUCTION AND PROCESSING (ALTERNATE METHOD)

DARS Attribute Category	Emission Factor Attribute	Explanation	Activity Data Attribute	Explanation	Emission Score
Measurement	4	The Norwegian Institute for Air Research measured emissions from magnesium production and developed a range of emission factors; this method uses the low end of that range. The implied emission factor for magnesium processing is based on mass balance.	3	State production of magnesium is based on national production and state production capacity; state processing of magnesium is based on national processing (as implied by emissions divided by emission factor) and state population.	0.12
Source Specificity	10	The emission factors were developed specifically for the intended source.	5	Magnesium production and casting levels are somewhat correlated to emission levels.	0.50
Spatial Congruity	5	The emission factor for magnesium production was developed for Norway, and factor spatial variability was found to be moderate to high.	3	States estimate state-level activity data based on national data; spatial variability is expected to be high.	0.15
Temporal Congruity	9	The emission factors are not expected to vary significantly over the course of a year.	8	States may use population data from the Census Bureau's most recent census data; temporal variability is expected to be low.	0.72
				Composite Score	0.37

7

REFERENCES

Abrahamson, D. 1992. "Aluminum and Global Warming." *Nature*, 356: 484.

American Iron and Steel Institute (AISI). 1993. *Annual Statistical Report: American Iron and Steel Institute, 1992.* AISI, Washington, DC.

C&EN (Chemical and Engineering News). 1994. "Top 50 Chemicals Production Rose Modestly Last Year." *Chemical & Engineering News*, vol. 72, number 15, p.13. April 11, 1994

C&EN. 1993. "Top 50 Chemicals Production Recovered Last Year." *Chemical & Engineering News*, vol. 71, number 15, p.11. April 12, 1993

C&EN. 1992. "Production of Top 50 Chemicals Stagnates in 1991." *Chemical & Engineering News.* 70(15): 17. April 13, 1992.

Freedonia Group, Inc. 1991. *Business Research Report B286: Carbon Dioxide.* The Freedonia Group, Incorporated. Cleveland, OH.

Gjestland, H. and D. Magers (1996) "Practical Usage of Sulphur [Sulfur] Hexafluoride for Melt Protection in the Magnesium Die Casting Industry," #13, *1996 Annual Conference Proceedings*, Ube City, Japan, International Magnesium Association.

Griffin, R.C. 1987. "CO_2 release from cement production, 1950-1985. In Marland, G., T.A. Boden, R.C. Griffin, S.F. Huang, P. Kanciruk, and T.R. Nelson. *Estimates of CO_2 Emissions from Fossil Fuel Burning and Cement Manufacturing, Based on the United Nations Energy Statistics and the U.S. Bureau of Mines Cement Manufacturing Data.* Report #ORNL/CDIAC-25, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee. May 1989. 643-680.

Hangebrauk, R.P., R.H. Borgwardt, and C.D. Geron. 1992. "Carbon Dioxide Sequestration." *EPA*, August 1992.

IPCC. 1997. *IPCC Guidelines for National Greenhouse Gas Inventories,* 3 volumes: *Vol. 1, Reporting Instructions; Vol. 2, Workbook; Vol. 3, Draft Reference Manual.* Intergovernmental Panel on Climate Change, Organization for Economic Co-Operation and Development. Paris, France. Internet address: http://iea.org/ipcc/general/inus1.htm

Maiss, Manfred and Carl A.M. Brenninkmeijer, 1998. "Atmospheric SF_6: Trends, Sources, and Prospects," *Environmental Science and Technology*, Vol. 32, pp. 3077-3086.

NIAR (1993) *SF$_6$ as a Greenhouse Gas: An Assessment of Norwegian and Global Sources and Global Warming Potential*, Norwegian Institute for Air Research, December, 1993.

ORNL. 1989. *Estimate of CO$_2$ Emissions from Fossil Fuel Burning and Cement Manufacturing, Based on the United Nations Energy Statistics and U.S. Bureau of Mines Cement Manufacturing Data.* ORNL/CDIAC-25, NDP-030. ORNL. Oak Ridge, Tennessee.

SRI (Stanford Research Institute). 1996. *1996 Directory of Chemical Producers, United States of America*. Menlo Park, CA: SRI International.

Thiemens, Mark H. and William C. Trogler. 1991. "Nylon Production: An Unknown Source of Atmospheric Nitrous Oxide. *Science*, vol. 251, page 932. February 22, 1991.

Tresouthick, S.W., and A. Mishulovich. 1990. "Energy and Environment Considerations for the Cement Industry," In conference proceedings *Energy and Environment in the 21st Century*. Massachusetts Institute of Technology, Cambridge, Massachusetts. March 26-28, 1990. B-110 to B-123

U.S. Department of Energy (U.S. DOE 1998) *Electric Power Annual 1997 Volume II.* U.S. Department of Energy, Energy Information Administration. Washington, DC. Internet address: http://www.eia.doe.gov/pub/pdf/electricity/0348972.pdf

U.S. EPA (U.S. Environmental Protection Agency). 1999. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 - 1997.* EPA 236-R-99-003. Internet address: http://www.epa.gov/globalwarming/inventory/1999-inv.html.

U.S. EPA (U.S. Environmental Protection Agency). 1998. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 - 1996*. EPA 236-R-98-006. Internet address: http://www.epa.gov/globalwarming/inventory/1998-inv.html.

U.S. EPA. 1993. *Proceedings -- Workshop on Atmospheric Effects, Origins, and Options for Control of Two Potent Greenhouse Gases: CF$_4$ and C$_2$F$_6$.* Sponsored by the Global Change Division, Office of Air and Radiation, EPA, April 21-22, 1993.

U.S. EPA. 1985. *Compilation of Air Pollutant Emission Factors, AP-42*. U.S. EPA, Washington, DC.

U.S. Geological Survey (USGS). 1998. *Mineral Commodity Summaries 1998*. U.S. Geological Survey, Minerals Information Service. Reston, VA. Internet address: http://minerals.er.usgs.gov/minerals/pubs/mcs/1998/

U.S. Geological Survey. 1997a. *Cement: Annual Report 1996.* U.S. Geological Survey, Minerals Information Service. Reston, VA, April, 1997. Internet address: http://minerals.er.usgs.gov/minerals/pubs/commodity/cement/index.html

U.S. Geological Survey. 1997b. *Lime: Annual Report 1996.* U.S. Geological Survey, Minerals
  Information Service. Reston, VA, 1997. Internet address:
  http://minerals.er.usgs.gov/minerals/pubs/commodity/lime/index.html

U.S. Geological Survey. 1997c. *Aluminum: Annual Report 1996.* U.S. Geological Survey,
  Minerals Information Service. Reston, VA, 1997. Internet address:
  http://minerals.er.usgs.gov/minerals/pubs/commodity/aluminum/index.html

U.S. Geological Survey. 1997c. *Bauxite: Annual Report 1996.* U.S. Geological Survey,
  Minerals Information Service. Reston, VA, 1997. Internet address:
  http://minerals.er.usgs.gov/minerals/pubs/commodity/bauxite/index.html

U.S. Geological Survey. 1997d. *Crushed Stone: Annual Report 1996.* U.S. Geological Survey,
  Minerals Information Service. Reston, VA, 1997. Internet address:
  http://minerals.er.usgs.gov/minerals/pubs/commodity/crushed-stone/index.html

U.S. Geological Survey. 1993e. *Soda Ash: Annual Report 1996.* U.S. Geological Survey,
  Minerals Information Service. Reston, VA, 1997. Internet address:
  http://minerals.er.usgs.gov/minerals/pubs/commodity/soda-ash/index.html